SUSY and Cold Dark Matter in ATLAS

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Non-baryonic cold dark is well established; WMAP fit gives

$$h = 0.72 \pm 0.05\,, \quad \Omega_b h^2 = 0.024 \pm 0.001\,, \quad \Omega_m h^2 = 0.14 \pm 0.02\,.$$

SUSY with R parity, $R = (-1)^{3B-3L+2S}$, provides $\tilde\chi_1^0$ as natural candidate.

$\Omega_{\tilde\chi} h^2$ calculated in mSUGRA by several groups. But SUSY breaking not understood; should not assume mSUGRA. Ωh^2 depends mainly on

- Mass of LSP $\tilde\chi_1^0$;
- Mass splitting between $\tilde\chi_1^0$ and, e.g., $\tilde\tau$;
- Composition of $\tilde\chi_1^0$, i.e., mixture of $\tilde\gamma, \tilde Z, \tilde H_1, \tilde H_2$.

Will concentrate for now on $\tilde\chi_1^0$ mass measurement in ATLAS. Other issues important but need development of new techniques.

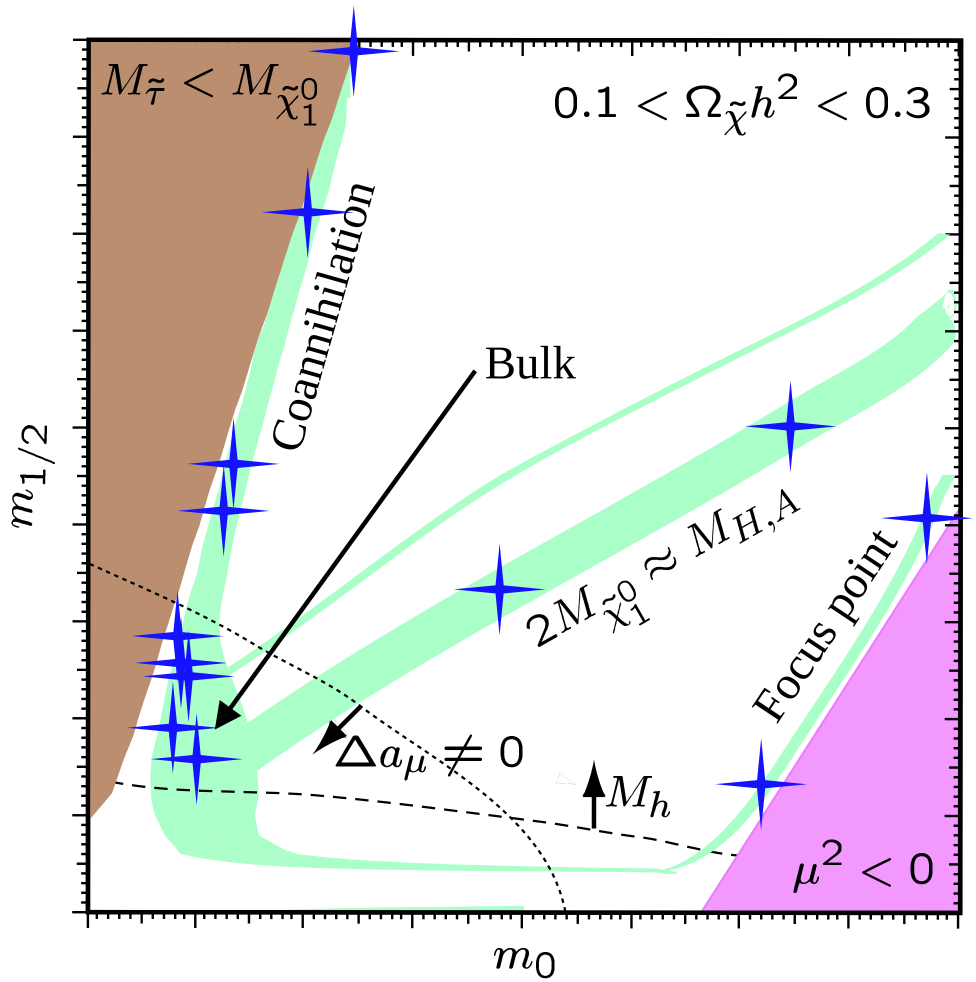
Use mSUGRA (no scales!) as guide. Several regions give right cold dark matter:

Bulk: bino $\tilde{\chi}_1^0$, light $\tilde{\ell}_R$ enhance annihilation.

Coannihilation: Light $\tilde{\tau}_1$ in equilibrium with $\tilde{\chi}_1^0$, giving $\tilde{\chi}_1^0\tilde{\tau}_1 \to \gamma\tau$.

Focus point: Small μ^2, so Higgsino $\tilde{\chi}_1^0$. Small FCNC.

Higgs funnel: H, A poles enhance annihilation.



ATLAS has only studied TDR Point 5 ($m_0, m_{1/2} = 100, 300\,\mathrm{GeV}$) and nearby points in bulk region for $\tilde{\chi}_1^0$ mass measurement.

$\tilde{\chi}_1^0$ is stable, neutral, and weakly interacting $\Rightarrow$ can only measure mass indirectly. For 3-body decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$, obviously have

$$M_{\ell\ell}^{\max} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$$

In mSUGRA bulk region, $\tilde{\chi}_2^0 \to \tilde{\ell}_R^\pm \ell^\mp \to \tilde{\chi}_1^0 \ell^\pm \ell^\mp$ dominates:

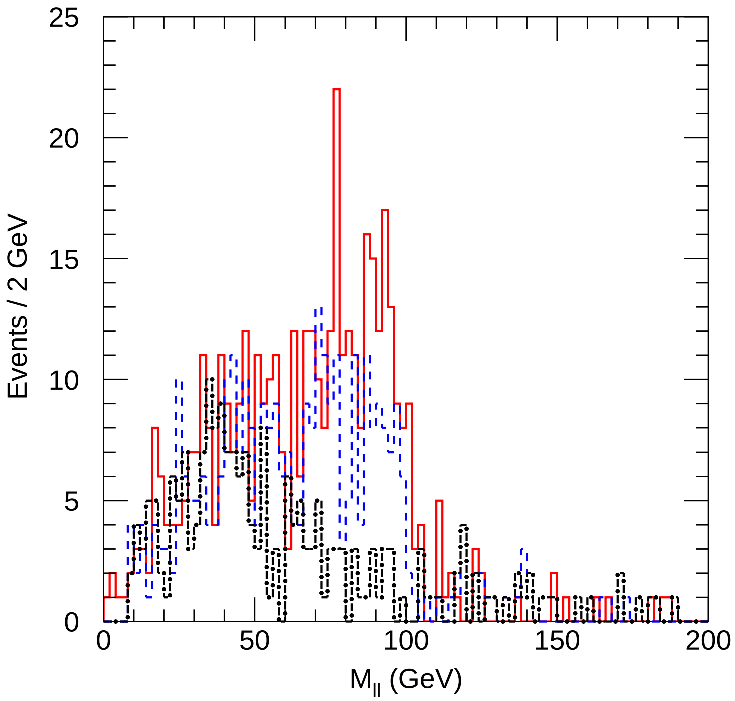
$$M_{\ell\ell}^{\max} = \frac{1}{M_{\tilde{\ell}}} \sqrt{(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\ell}}^2)(M_{\tilde{\ell}}^2 - M_{\tilde{\chi}_1^0}^2)}$$

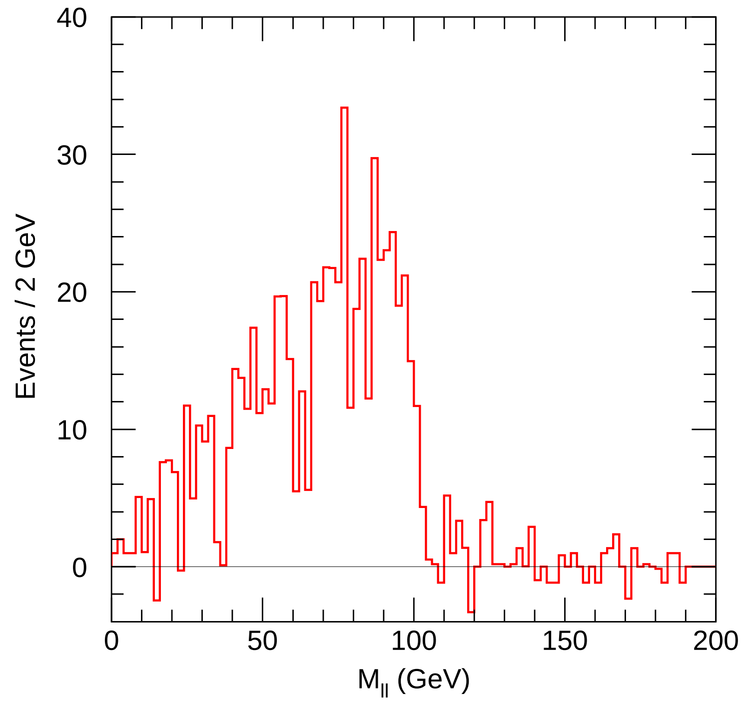
Exercise: Show this. Neglect widths and lepton masses; use a boost.

Slepton mixing would induce $\mu \to e\gamma$, so expect signal only in e^+e^-, $\mu^+\mu^-$. Independent decays of $\tau^+\tau^-$, $t\bar{t}$, $\tilde{\chi}_1^+\tilde{\chi}_1^-, \ldots$, also give $e^+\mu^-$, μ^+e^-.

ATLAS is designed to have good acceptance for both e and μ. Then independent decay backgrounds cancel in $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$.

$\mu^+\mu^-$, e^+e^-, $e^\pm\mu^\mp$ distributions from Athens full simulation ($5\,\mathrm{fb}^{-1}$). See 17% acceptance difference and 2% energy difference from full simulation and reconstruction (Athena 6.0.3):





Calibrate with Z decays. Then should measure $\ell^+\ell^-$ endpoint to $\sim 0.1\%$ with high statistics.

Longer decay chains allow more measurements. Main source for $\tilde{\chi}_2^0$ at TDR Point 5 and full simulation point is

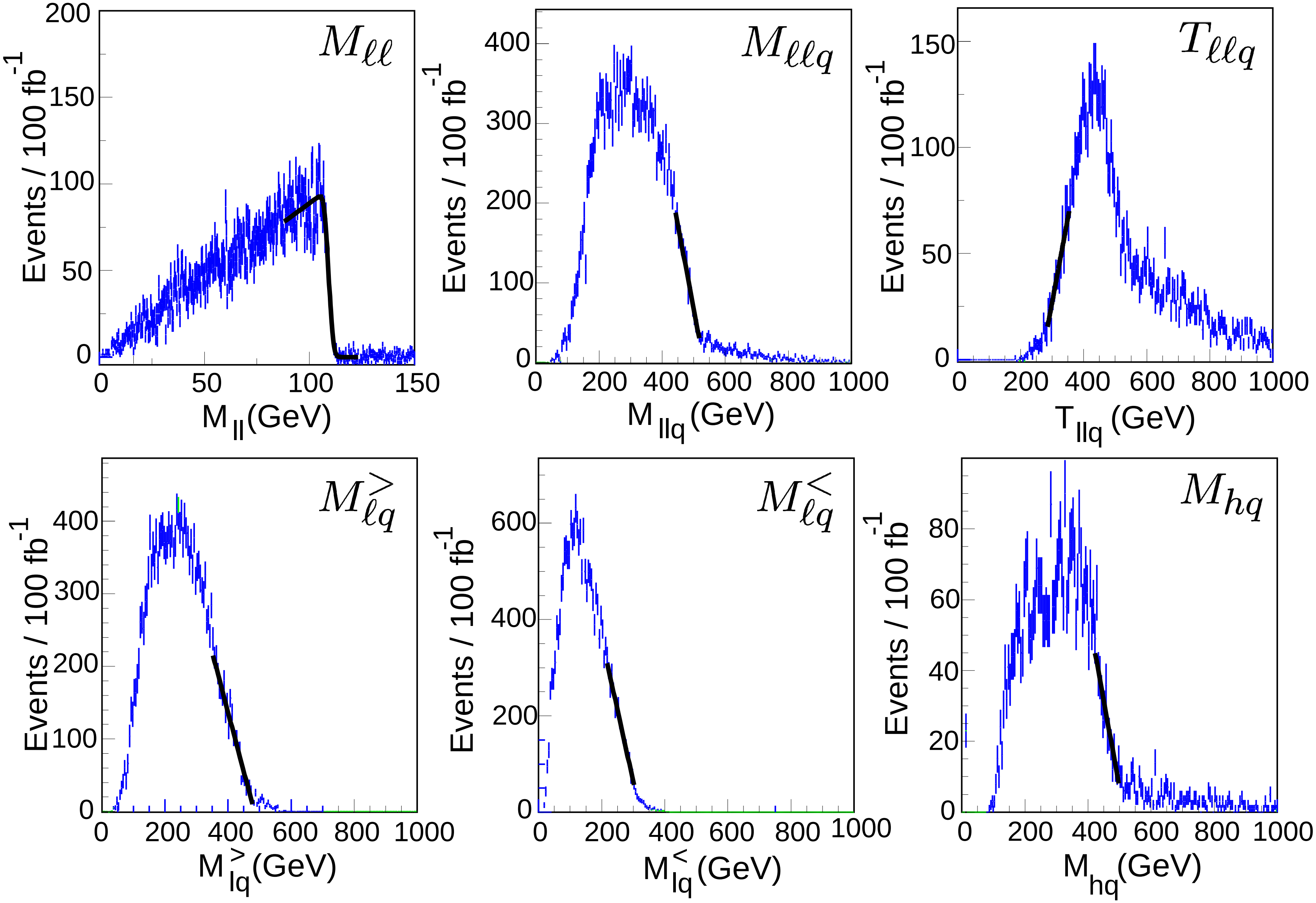
$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\ell}_R^\pm \ell^\mp q \to \tilde{\chi}_1^0 \ell^\pm \ell^\mp q$$

In mSUGRA light $\tilde{\ell} \Rightarrow$ small $m_0 \Rightarrow M_{\tilde{g}} \gtrsim M_{\tilde{q}}$. Hence expect hardest jets to come from $\tilde{q}$.

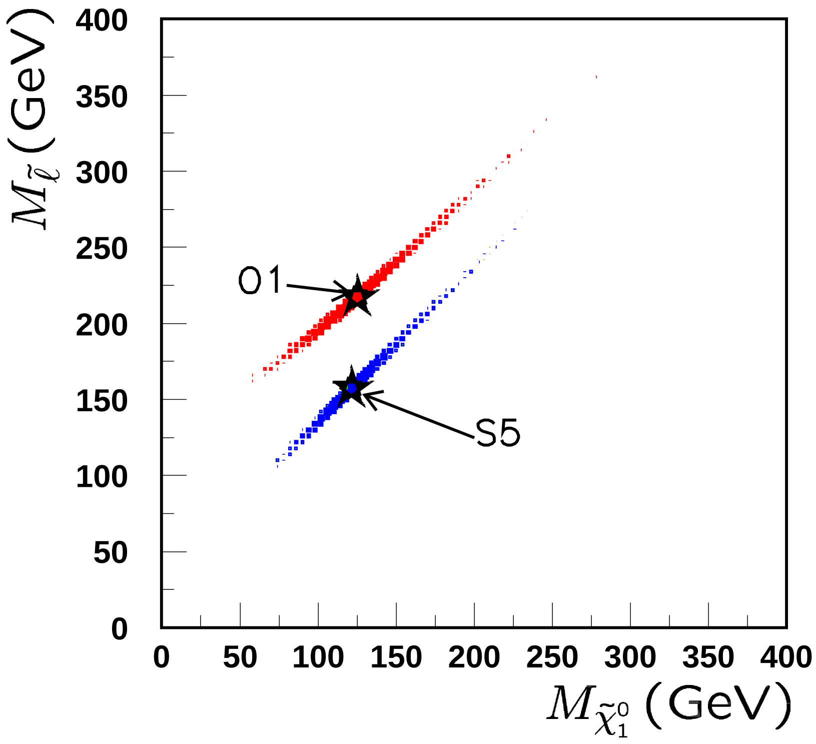
Make standard multijet, $\not{E}_T$, and M_{eff} cuts and also require $\ell^+\ell^-$. Then combine each of two hardest jets with leptons to form:

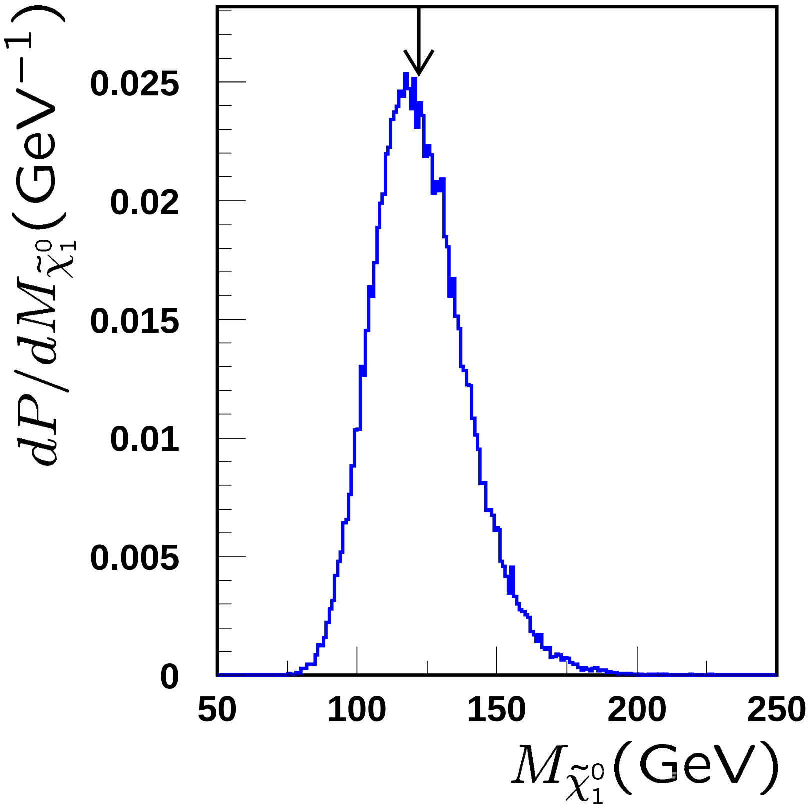
- $M_{\ell\ell q}$: smaller $\ell\ell j$ mass, so less than endpoint.
- $M_{\ell q}^>$: larger ℓj mass with same jet.
- $M_{\ell q}^<$: smaller ℓj mass with same jet.
- $T_{\ell\ell q}$: larger $\ell\ell j$ mass for $M_\ell > M_{\ell\ell}^{\max}/\sqrt{2}$.

Note $M_{\ell\ell}$ cut needed for non-zero threshold $T_{\ell\ell q}$. Gluon radiation pushes events below threshold. Results from Allanach et al.:


$M_{\ell\ell}$
Events / 100 fb^{-1}
M$_{ll}$(GeV)
$M_{\ell\ell q}$
M$_{llq}$ (GeV)
$T_{\ell\ell q}$
T$_{llq}$ (GeV)
$M_{\ell q}^{>}$
M$_{lq}^{>}$(GeV)
$M_{\ell q}^{<}$
M$_{lq}^{<}$(GeV)
M_{hq}
M$_{hq}$(GeV)

Estimate errors on fitted endpoints. Select $M_{\tilde{q}} > M_{\tilde{\chi}_2^0} > M_{\tilde{\ell}} > M_{\tilde{\chi}_1^0}$ at random, compute endpoints and χ^2, and weight with probability:





For this point, measure relative masses to $\sim 1\%$ and $\tilde{\chi}_1^0$ mass to $\sim 10\%$ since $M_{\tilde{\chi}_1^0} \approx \frac{1}{6} M_{\tilde{q}}$.

ATLAS

Expect $\tilde{\chi}_2^0 \to \tilde{\ell}\ell$ to be open in bulk and coannihilation regions. Also expect $\tilde{q}_L \to \tilde{\chi}_2^0 q$ to be dominant source of $\tilde{\chi}_2^0$ in mSUGRA.

Project 1: Assess error on $\tilde{\chi}_1^0$ mass throughout bulk and coannihilation regions based on $\ell^+\ell^-$ channel.

Might analyze $\ell^+\ell^-$ signal for each "post-WMAP" benchmark point:

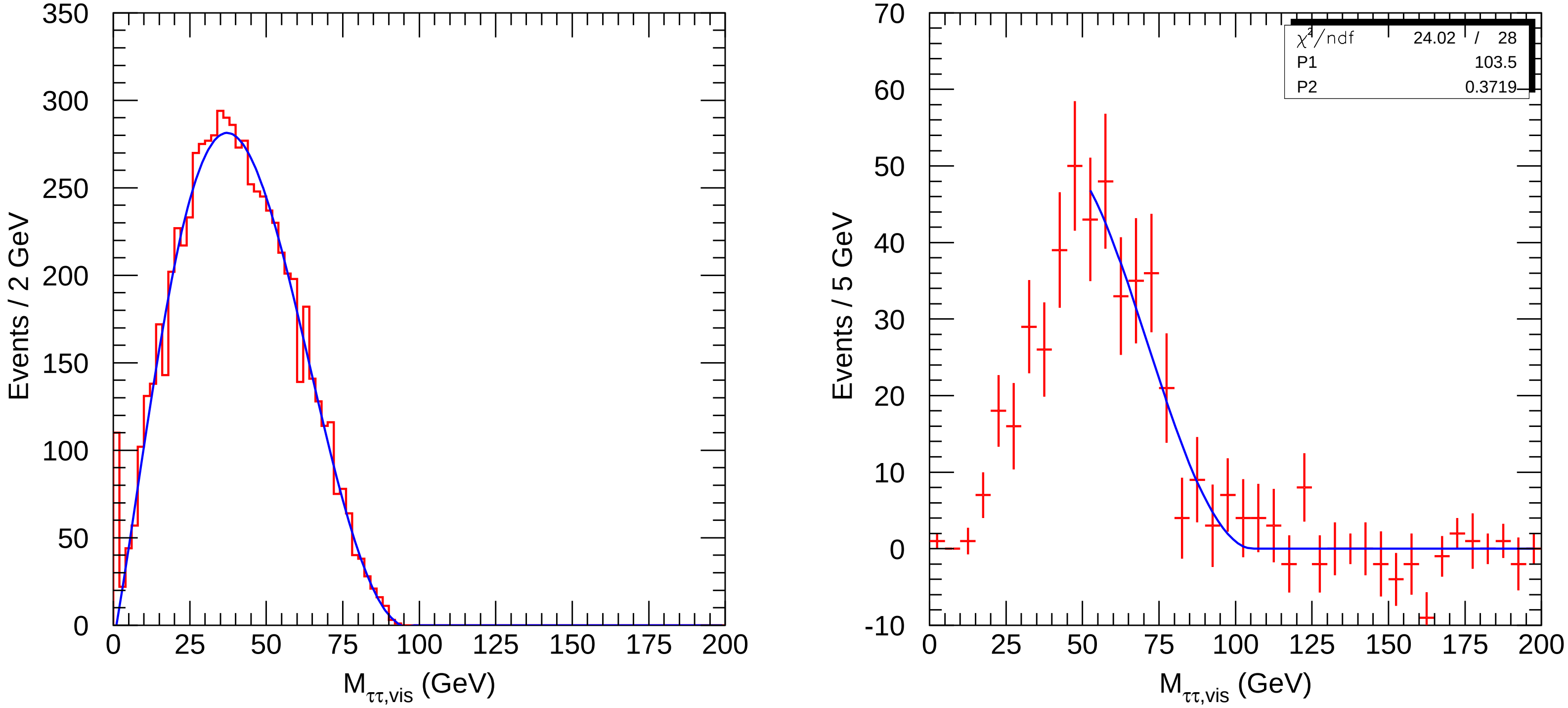
- Determine signal, including SUSY production cross section, branching ratios, acceptance.
- Study Standard Model backgrounds, at least $t\bar{t}$, Wj, Zj, and WW.
- Estimate errors (mainly systematic for Point 5 but not if heavy masses or small branching branching ratios).

Straightforward application of existing SUSY analysis methods, but informative.

$\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau$ can dominate over $\tilde{\chi}_2^0 \to \tilde{\ell}\ell$ if $\tan\beta \gg 1$. Two problems:

- Must identify hadronic τ decays $\Rightarrow$ background from QCD jets.
- Cannot reconstruct $\tau\tau$ mass. Must fit shape of visible mass.

Fit $M_{\tau\tau,\mathrm{vis}}$ Monte Carlo shape (left) to $\tau^+\tau^- - \tau^\pm\tau^\pm$ distribution (right) with full simulation gives $M_{\tau\tau}^{\max} = 103.5 \pm 4.9\,\mathrm{GeV}$; c.f, $98.3\,\mathrm{GeV}$:



Project 2: Assess errors on $\tilde{\chi}_1^0$ mass and $\tilde{\tau}$ mass using hadronic $\tau\tau$ decays.

Significantly harder than Project 1. Some main issues:

- Understand hadronic τ identification and measurement.
- Understand role of τ polarization.
- Modify Atlfast to describe τ acceptance and measurement.
- Fit complex shapes rather than simple edges.

Note: Even if $\ell^+\ell^-$ is measurable, $\tau^+\tau^-$ contains additional information about SUSY model and should be studied.

Hadronic τ decays are important signature for new physics. Atlfast uses generator information to tag τ's perfectly [sic!]. Athena τ reconstruction needs more effort.

In focus point region sleptons are heavy, so $\tilde{\chi}_2^0 \not\to \tilde{\ell}\ell, \tilde{\tau}\tau$.

Mass spectrum for direct $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+\ell^-$ dominated by Z pole. Endpoint determines $M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} < M_Z$. Acceptance corrected shape $\Rightarrow$ also $M_{\tilde{\chi}_1^0}$, which modifies phase space.

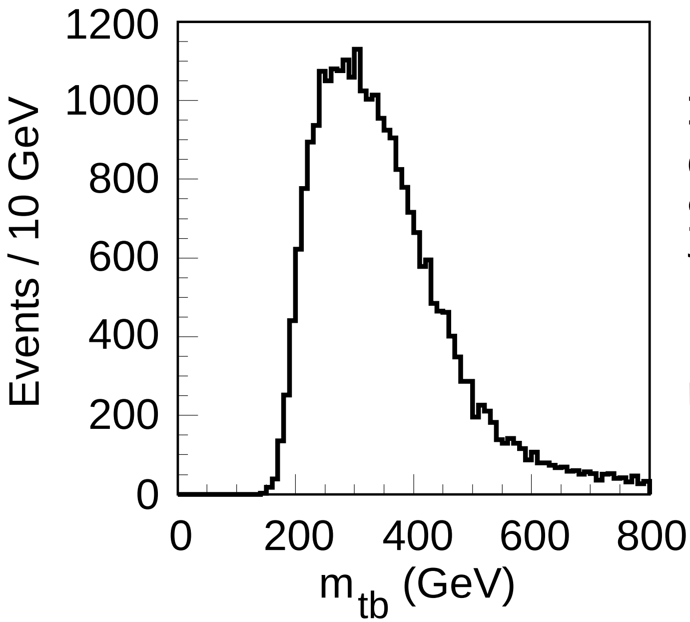
Project 3: Assess error on $\tilde{\chi}_1^0$ mass in focus point region using $M_{\ell\ell}$ shape from $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+\ell^-$.

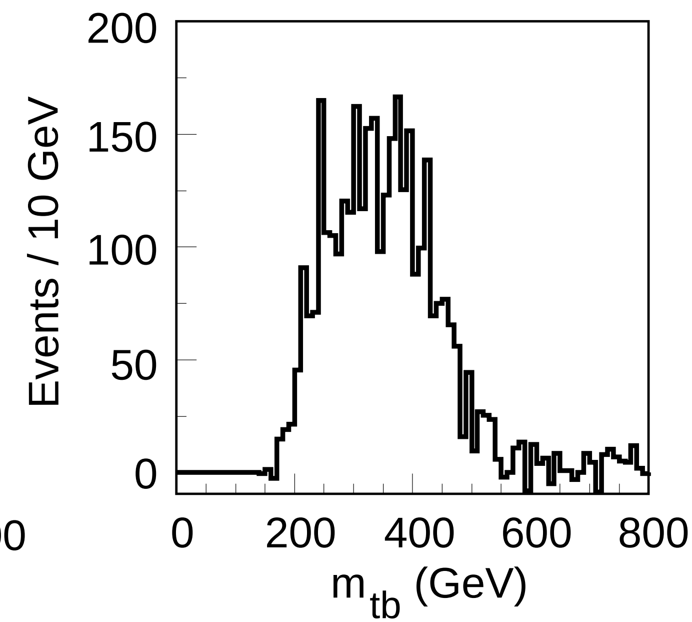
New type of analysis. Some issues:

- Determine sensitivity of shape to $M_{\tilde{\chi}_1^0}$.
- Understand effects of acceptance on $M_{\ell\ell}$ distribution.
- Expect background to be small after flavor subtraction, but $\ell^+\ell^-$ branching ratio is only $2 \times 3\%$.

Current Atlfast is probably adequate, at least to start.

For larger $m_{1/2}$ in focus point region, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z, \tilde{\chi}_1^0 h$, so no $\ell^+\ell^-$ shape information. But then $\tilde{g} \to \tilde{\chi}_i^0 b\bar{b}$ or $\tilde{g} \to \tilde{\chi}_i^- t\bar{b}$ has both shape and endpoint. Sideband subtraction can find endpoint for latter:





Project 4: Use hadronic shape from $\tilde{g} \to \tilde{\chi} q\bar{q}'$ to measure masses.

Issues: b tagging, jet resolution, combinatorial background, acceptance corrections. New type of analysis, probably not trivial.

Summary

After WMAP non-baryonic cold dark matter is well established. Requires extension of Standard Model.

SUSY provides natural candidate, $\tilde{\chi}_1^0$. Relic density calculable in any specific model, but should measure relevant quantities directly.

First question: can ATLAS can measure $\tilde{\chi}_1^0$ mass? Seems feasible to address this; mixture of easier and harder analyses.

Measuring $\tilde{\tau}_1 - \tilde{\chi}_1^0$ splitting in coannihilation region involves soft τ's. Likely goal of next SUSY full simulation study.

Composition of $\tilde{\chi}_1^0$ requires study of rates and branching ratios. Trivial to compare Monte Carlo with itself, but realistic analysis needs additional thought.

Should aim to understand cold dark matter with ATLAS.